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Paper No. 14

DYNAMICS OF THE SKYLAB WASTE TANK SYSTEM

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ABSTRACT

The waste tank venting system is a source of contamination for the Skylab space environment. Therefore the possibility for an assessment of the vapor flow rate under various conditions during and after liquid dumps is desirable. The dynamics of the Skylab waste tank venting system is discussed in terms of convenient subsystems. Some representative test results are reported and the experimental observations during a waste tank simulation test are connected with the mathematical model. During experimentation with CO_2 purges it was found that the sublimation rate of ice can be considerably changed by the presence of other gases.

INTRODUCTION

The Skylab waste tank is a continuous source of contamination of the space environment. For this reason it is important to know the rate of vapor flow which is expected under different circumstances. Of particular importance are the quasi steady state vapor flow rate and the time dependence of the flow rate during and after waste dumps.

The basic parameters which allow such prediction were collected during a simulation test of the Skylab waste tank performance at Martin Marietta's Denver facility. A model is conveniently developed by considering the total waste tank as an interplay between a number of subsystems which can be treated rather independently because their interaction with one another is either weak or can be readily described.

As an example the nonpropulsive vents of the waste tank can be treated as such a subsystem. Another example is the pile of ice, stored on the baffle of the waste tank. By virtue of its heat capacity it acts as a "temperature buffer" for additional liquid dumps. A buffer with negligible heat capacity is given by the considerable volume of the waste tank which acts as a "pressure buffer."

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DESCRIPTION OF THE WASTE TANK

The waste tank which was used for simulation is a metal container with a total volume, $V=80.4\ m^3$ which is divided into three compartments as shown in figure 1. The compartments are separated by finely meshed screens which prevent solid particles >1μm from passing. The top compartment has a volume $V_1=7.3\ m^3$ and contains a baffle fabricated of relatively thin plastic material. The baffle supports the ice pile which forms during liquid dumps through a nozzle situated at the top of the upper compartment and prevents the ice from coming into contact with the screen. As indicated in figure 1 the ice pile is partially enclosed by the baffle and for this reason the radiative heat transfer from the temperature controlled walls of the top compartment to the ice pile is partially attenuated by the baffle. The area of the screen is about $A=11\ m^2$. The middle compartment has about ten times the volume of the upper and lower compartment. The lower compartment is open to the outside of the waste tank by two pipes of length L=34 cm and inner diameter of d=3.81 cm, corresponding to a cross sectional area of 11.4 cm^2 for each pipe.

In order to simulate space conditions the entire waste tank was placed into a still larger vacuum system of high pumping speed. Since the flow conductance of the wire screens is large compared to the combined conductance of the two venting pipes one finds usually only small pressure differences between the three waste tank compartments.

GENERAL RELATIONS AND IDENTIFICATION OF SUBSYSTEMS

Next the equations will be developed which govern the dynamic behavior of the waste tank. In figure 1 the pressure in the upper compartment of volume V_1 is P_1, while the pressure in the remainder of the waste tank (volume V_2) is designated as P. The pressure difference across the top screen is

$$\Delta P=P_1-P \tag{1}$$

It is caused by the wire screen of conductance $C(k_1)$ in [ℓsec^{-1}]. The symbol (k_1) is attached as a reminder that the screen conductance is a function of the composition of the gas which passes through the screen. With these notations the flow characteristics of the waste tank can be described by the following set of equations:

$$V_1\dot{P}_1=Q_{in}-C(k_1)\Delta P \tag{2}$$

$$V_2\dot{P}=C(k_1)\Delta P-Q_{out}(k_2) \tag{3}$$

Q_{in} in equation 2 pertains to the incoming gas flow rate which is produced in the upper compartment either by the sublimation of the stored ice and/or by the dumping of gases or liquids through the inlet nozzle. Q_{in} therefore represents the generating system for the gas flow and can be singled out as a subsystem. Obviously Q_{in} depends upon a number of parameters such as the mass and spacial distribution of the stored ice on the baffle and the heat transfer from the surroundings to the ice pile. On the other hand, Q_{in} is for most practical purposes independent of the tank pressure P, with the exception of a strong pressure dependence in the vicinity of the triple point pressure.

Q_{out} pertains to the vapor flow rate through the two venting pipes which represent another subsystem. Q_{out} is mainly a function of the tank pressure P and this functional dependence will be intensively studied. The symbol (k_2) is to indicate that Q_{out} is a function of the gas composition. In a dynamic situation (k_1) can be different from (k_2).

The total volume V of the waste tank can be regarded as a separate subsystem. The pressure P depends upon Q_{in} and Q_{out} in a simple manner. Addition of equations 2 and 3 and use of equation 1 leads to:

$$V_1\dot{P}_1+V_2\dot{P}=V\dot{P}[1+(V_1/V)(\Delta\dot{P}/\dot{P})]\approx V\dot{P}$$

Therefore

$$V\dot{P}\approx Q_{in}(k_1)-Q_{out}(k_2) \tag{4}$$

In a quasi steady state condition:

$$Q_{in}=Q_{out} \tag{5}$$

Since the tank pressure P must build up through the contribution $(Q_{in}-Q_{out})$ as a function of time, the volume V of the waste tank acts as a "pressure buffer."

MEASUREMENT OF Q_{in}

Although the pressure drop across the screen is usually of little significance it can be used as a measure for the vapor flow rate Q_{in}. The passages through the screen are very small, of the order of 1μm and as a consequence the vapor flow through the screen is molecular in nature as long as the tank pressure is below 20 torr. In the molecular flow regime the screen conductance C is independent of pressure and can be characterized by

$$C=g\cdot(T/M)^{1/2}\ [\ell sec^{-1}] \tag{6}$$

g is a geometrical factor which depends upon the structure of the screen, T is the absolute temperature of the gas at the screen and M is the molar weight.

According to equation 2 one finds for a quasi steady state condition:

$$Q_{in}=C\Delta P \ [\text{torr } \ell \sec^{-1}] \tag{7}$$

By measuring the gas flow rate through the inlet nozzle with a flow meter and the pressure drop across the screen, the screen conductance can be determined experimentally. Such an experiment was carried out at room temperature with CO_2 and N_2 gas. The result is shown in figure 2 where ΔP in [mtorr] is plotted versus Q_{in} in [torr $\ell\sec^{-1}$]. As expected a linear relationship results which is different for the two gases. One can note, that the straight lines representing the best fit to the experimental data do not cross the origin of the coordinate system as is required by equation 7. Either the pressure indicator for ΔP has a bias such that the measured value ΔP_m should be replaced by

$$\Delta P=\Delta P_m+\eta \ [\text{torr}] \tag{8}$$

or the flow meter is biased and the measured value Q_m should be replaced by Q, where

$$Q=Q_m+\Delta Q \ [\text{torr } \ell \sec^{-1}] \tag{9}$$

or a combination of the two errors. Whatever the bias errors may be they do not impair the accuracy when the screen conductance is obtained from the slopes:

$$C=\frac{dQ}{d\Delta P} \tag{10}$$

With this procedure one obtains for room temperature the following values:

$$C(CO_2)=2.33\text{x}10^4 \ [\ell \sec^{-1}] \tag{11}$$

$$C(N_2)=3.02\text{x}10^4 \ [\ell \sec^{-1}]$$

Note that under equal conditions one should find according to equation 6

$$C(CO_2)/C(N_2)=[M(N_2)/M(CO_2)]^{1/2}=(\frac{28}{44})^{1/2}=0.796 \tag{13}$$

By comparison the experimental values from equation 11 and 12 yield

$$C(CO_2)/C(N_2)=2.33\text{x}10^4/3.02\text{x}10^4=0.772$$

in satisfactory agreement with the theoretically expected value.

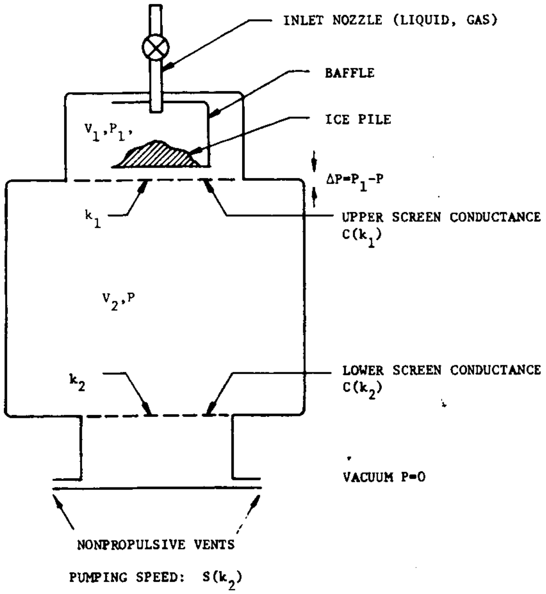

Figure 1. Schematic of the Waste Tank Configuration

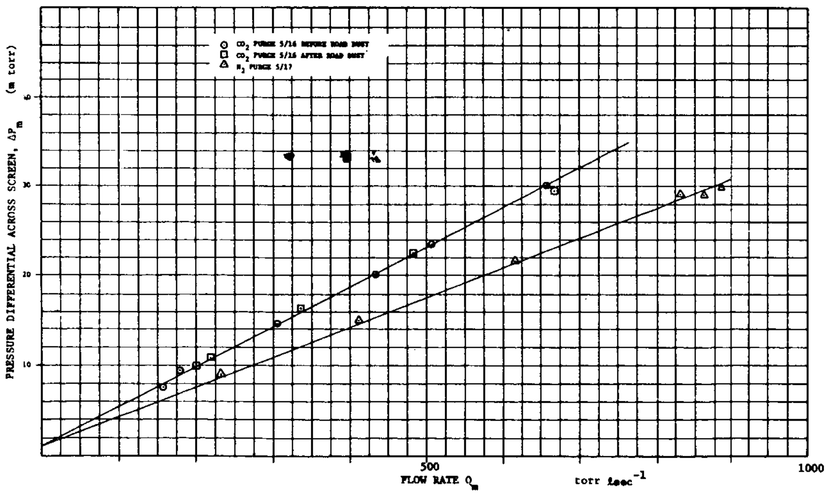

Figure 2. Pressure Differential Across Screen ΔP_m Versus Flow Rate, Q_m (ΔP_m, Q_m as Measured)

The error is 3 percent.

Using the most reliable experimental values at a temperature distribution closest to normal operational conditions one obtains from the data in figure 3 the following value:

$$C(CO_2)=2.68\times10^4\ [\ell sec^{-1}]$$

and consequently

$$C(H_2O)=2.68\times10^4\cdot(44/18)^{1/2}$$
$$=4.18\times10^4\ \ell sec^{-1} \tag{15}$$

Through the calibration procedure of the screen conductance the easily measured quantity ΔP can be directly related to the vapor flow rate in the waste tank. The screen conductance can also be obtained for other gases and mixtures of gases.

Q_{out} AS A FUNCTION OF TANK PRESSURE

In this section the vapor flow rate through the combined action of the two nonpropulsive vents will be investigated as a function of the waste tank pressure P. It is assumed that a vacuum exists outside of the waste tank with an external pressure $P_{ext}<10^{-6}$ torr.

When the pressure inside the tank equals the external pressure the flow rate is obviously zero. For $P<10^{-3}$ torr the mean free path of the gas molecules is greater than the inside diameter of the pipes and one has a molecular flow. For $P>10^{-3}$ torr the flow becomes laminar and viscous in character and the flow velocity at the end of the pipe is steadily increasing with increasing pressure. When the flow velocity reaches the Mach number M=1, a shock wave will reach the exit of the vent, at which point the maximum pumping speed for the vent has been reached. With increasing pressure only the density of the gas can increase and as a consequence the flow is "choked" and Q_{out} becomes proportional to the tank pressure P.

More quantitatively in the region of molecular and laminar flow one can approximate Q_{out} by the use of Knudsen's semiempirical formulation

$$Q_{out}=S_L(P)\cdot P \tag{16}$$

with

$$S_L(P)=\frac{D^3}{L}\left\{3.27\times10^{-2}\,\frac{PD}{\eta}+7.62\left(\frac{T}{M}\right)^{1/2}\,\frac{1+0.147\left(\frac{T}{M}\right)^{1/2}\frac{PD}{2\eta}}{1+0.181\left(\frac{T}{M}\right)^{1/2}\frac{PD}{2\eta}}\right\} \tag{17}$$

with the pumping speed for laminar flow, S_L, in $[\ell sec^{-1}]$, the inner pipe diameter D in [cm], the length of the pipes L in [cm], the viscosity η in [poise], the molar weight M in [g/mole], the absolute temperature T in [°K] and the pressure P in [torr]. Inserting the values for water vapor one finds for the combined action of the two pipes approximately:

$$S_L(P)=2.21x10^3P+39 \ [\ell sec^{-1}] \quad (18)$$

In general a theoretical calculation of the flow rate for Mach numbers close to unity is difficult to achieve. Gershman and Lannon, (Reference 1), subsequently referred to as (G&L) have carried out such calculations taking into account the friction loss near the duct entrance and the heat exchange of the flowing gas with the pipe walls. From their results one can conclude that an extrapolation of the flow rate to zero flow intercepts the pressure axis at about 0.2 torr. This result holds for water vapor as well as for nitrogen. The reason can be traced to the socalled "head loss," a pressure loss, which is caused by the friction of the flowing gas with the pipe walls. Since the flow rate must converge to zero for diminishing pressure the curve representing $Q_{out}(P)$ must end up at the origin of the coordinate system. The pressure region between 0.1 and 0.3 torr is of importance because the quasi steady state pressure is usually in this range. An accurate knowledge of the flow rate as a function of pressure yields therefore important information about the contamination contribution of the two nonpropulsive vents inbetween dumps.

We shall now use experimental data to determine $Q_{out}(P)$ explicitly. In figure 4 the pressure drop ΔP across the top screen under a steady state condition is plotted versus the tank pressure P during an admission of CO_2 gas. The data indicates that the flow is indeed choked. When the experimental values for ΔP are extrapolated to $\Delta P=0$ the pressure axis is intercepted at about 0.2 torr as predicted by (G&L) for N_2 and H_2O gas. Combining the results shown in figure 3 and 4 one obtains the bias free result

$$S(CO_2)= \frac{dQ}{dP} = \frac{dQ}{d\Delta P} \cdot \frac{d\Delta P}{dP} =C(CO_2)\cdot \frac{d\Delta P}{dP} =331 \ [\ell sec^{-1}] \quad (19)$$

During numerous water dumps P_m and ΔP_m have been registered. Therefore the time derivative of P_m, $\dot{P}_m$ is also known. One has to allow, however, for the possibility that the measured values P_m and ΔP_m are offset by biases in the instruments as indicated by equation 8 and/or by

$$P=P_m+\eta \quad (20)$$

But one can notice that

Reference 1 Gershman and L. E. Cannon, Performance Analysis for the Skylab Waste Tank Nonpropulsive Vent System, Presented to SAE Aerospace Fluid Power and Control, Technology Meeting, San Francisco, California, 16 October 1972

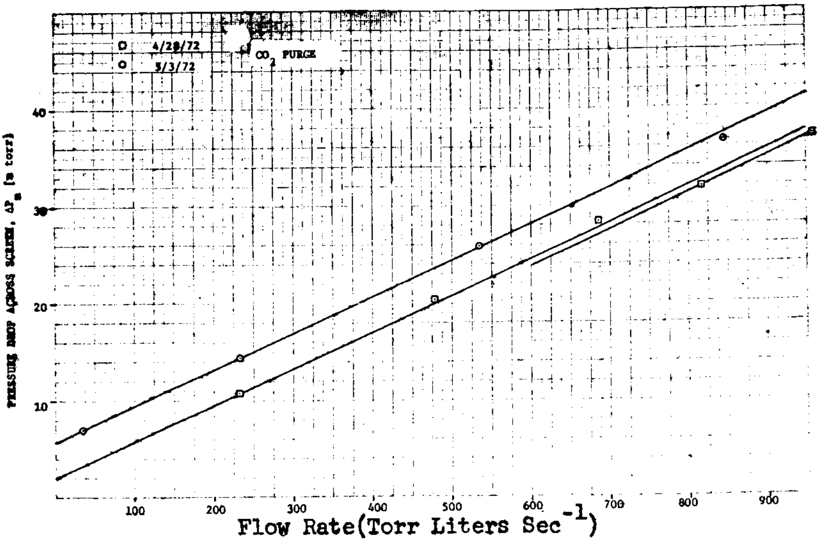

Figure 3. Determination of the Screen Conductance With CO_2 Gas

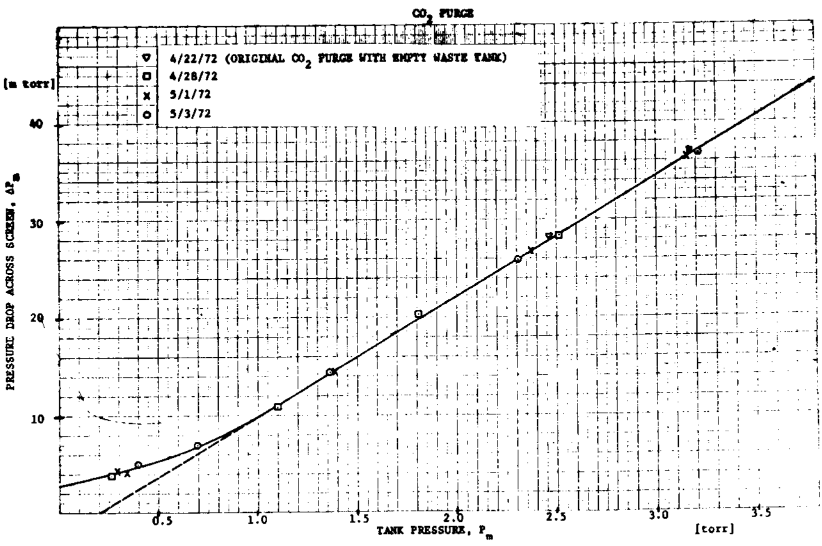

Figure 4. Relation Between Tank Pressure and Pressure Drop Across Screen

$$\dot{P}_m = \dot{P} \tag{21}$$

Using equation 3 one can calculate Q_{out} as

$$\begin{aligned} Q_m &= C(\Delta P + \eta) - V_2 \dot{P} \\ &= (C\Delta P - V_2 \dot{P}) + C\eta = Q_{out} + C\eta \end{aligned} \tag{22}$$

In table I data and resulting calculations are shown for a 8.3 lb condensate dump on 4/28/72. The result is plotted in figure 5. For pressures >0.6 torr the data yield

$$S(H_2O) = \frac{dQ_m}{dP_m} = \frac{dQ}{dP} = 455 \ [\ell sec^{-1}] \tag{23}$$

a value which is free of bias error. For P<0.6 torr the experimental points deviate from the linear relation. A great number of water dumps have been evaluated and show exactly the same behavior. It would serve no useful purpose to add more experimental points. One can, however, state that the behavior shown in figure 5 is highly reproducible. Figure 6 is a close-up of figure 5 exhibiting more distinctly the deviation of the data points at low pressure from a straight line. If the deviation is designated as δp a plot of log δp versus P_m shows an empirical relation for $\delta p(P_m)$ as shown in figure 7 which can best be expressed in the form

$$\delta p = \delta p_o \ \exp[-\alpha(P - \delta p_o + \delta p)] \tag{24}$$

where use has been made of the fact that the intercept of the linear extrapolation of Q_{out} crosses the P-axis at

$$\delta p_o = 0.2 \ [torr] \tag{25}$$

The value for α is

$$\alpha = 1.68 \ [torr^{-1}] \tag{26}$$

The dashed extrapolation of the curve connecting the experimental data in figure 6 is accomplished through the use of the dashed line in figure 7.

If one follows this procedure one can determine the instrumental biases ε and η. One finds

$$\begin{aligned} \varepsilon &= -0.05 \ [torr] \\ \eta &= 1.86 \ [m\ torr] \end{aligned} \tag{27}$$

Using these corrections the two columns P and Q_{out} in table I have been calculated. The result is shown in figure 6.

Table I. Data and Evaluation of Event 4-5-13
8.3 Lb Condensate Dump on 4/28/72

P_m [torr]	ΔP_m [m torr]	$-\dot{P}$ [torr sec^{-1}]	$-V_2\dot{P}$ [torr ℓsec^{-1}]	$C\Delta P_m$ [torr ℓsec^{-1}]	Q_m [torr ℓsec^{-1}]	P [torr]	Q_{out} [torr ℓsec^{-1}]
1.852	12.6	3.58×10^{-3}	261	526	787	1.802	709
1.750	12.1	3.46	252	506	758	1.700	680
1.573	11.4	2.67	195	477	672	1.523	594
1.309	10.2	1.84	134	427	561	1.259	483
1.209	9.8	1.55	113	410	523	1.159	445
1.125	9.3	1.32	96	390	486	1.075	408
1.020	8.4	1.00	73	352	425	0.970	347
0.864	7.8	0.72	52.5	326	378.5	0.814	300
0.721	6.26	0.44	32.1	263	295.1	0.671	217
0.616	5.49	0.25	18.2	229	247.2	0.566	169
0.558	5.13	0.16	11.7	215	226.7	0.508	149
0.514	4.83	0.12	8.8	202	210.8	0.464	133
0.410	3.87	0.10	7.3	162	169.3	0.360	91
0.359	3.54	0.07	5.1	148	153.1	0.309	75
0.327	3.35	0.02	1.5	140	141.5	0.277	64
0.280	3.11	-	-	130	130	0.230	52

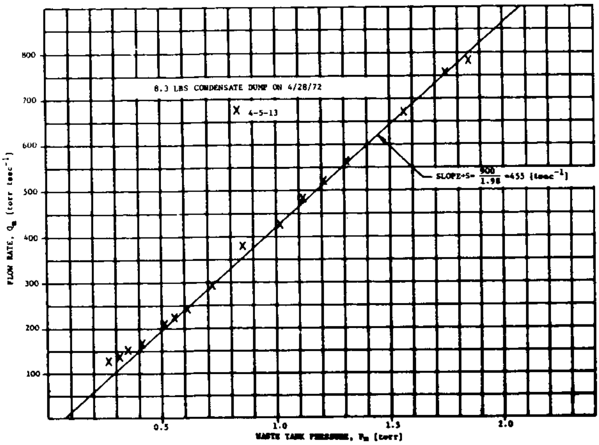

Figure 5. Determination of the Pumping Speed of the Waste Tank Venting System for Water Vapor

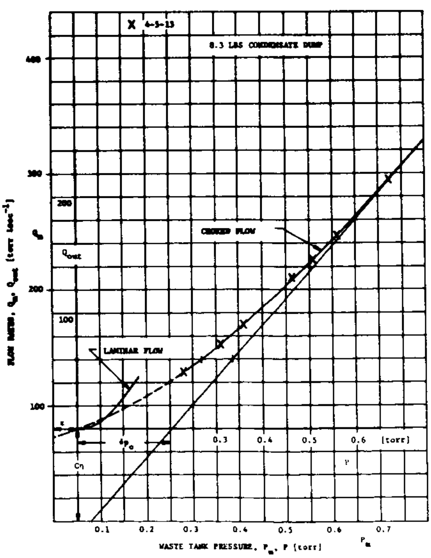

Figure 6. Flow Rate Vs Waste Tank Pressure for Water Vapor at Low Pressure

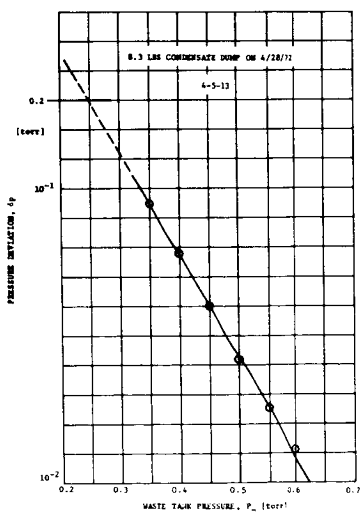

Figure 7. Pressure Deviation From Linearity As a Function of Waste Tank Pressure

It is worthwhile to note that (G&L) find theoretically for water vapor at temperatures of 5°C and 60°C respectively, the following values for the pumping speed.

$$S_{th}=462 \ \ell sec^{-1}$$

$$S_{th}=454 \ \ell sec^{-1}$$

The experimental value for S obtained during the waste tank simulation test is between the above mentioned values:

$$S_{exp}=455 \ \ell sec^{-1}$$

This agreement lends credibility also the value of the pressure loss $\delta p_o=0.2$ torr.

In order to express Q_{out} in a mathematical formula one can use equation 24 to determine $\delta p(P)$ and subsequently calculate Q_{out} from

$$\begin{aligned} Q_{out} &= S[P-(\delta p_o-\delta p)] \\ &= \{S[1-(\delta p_o-\delta p)/P]\}P = S_c(P)\cdot P \end{aligned} \tag{28}$$

Here $(\delta p_o-\delta p)$ is the pressure loss due to friction and $S_c(P)$ is the pumping speed for the two pipes for choked flow.

For the purpose of a comparison the flow rate for molecular and laminar flow as given in equation 18, is introduced into figure 6. Below 0.06 torr the flow rate for molecular and viscous flow is below the empirical extrapolated curve for choked flow. It is threrfore reasonable to assume, that for pressures below the transition pressure $P_t=0.06$ torr the flow rate is limited by the lower laminar flow rate. If this suggestion is accepted Q_{out} can be represented in the form:

$$Q_{out}=S(P)P \tag{29}$$

with

$$S(P)=S_L[1-\int\delta(P-P_t)dP]+S_C\int\delta(P-P_t)dP \tag{30}$$

where the transition pressure P_t can be obtained from

$$S_L(P_t)=S_c(P_t) \tag{31}$$

One can check Q_{out} at low pressure by using the observation that in a quasi steady state condition the weight loss of the ice pile in the waste tank is about 6 lbs per day. It has been observed, that under these conditions the tank pressure is about 0.15 torr. According to figure 6 or equations 24 and 28 the corresponding value for Q_{out} is

$$Q(0.15)\approx 30 \text{ torr } \ell sec^{-1}$$

This flow rate corresponds to a weight loss over a 24 hour period of

$$\frac{30x3600x24x18}{760x22.4x454}=6 \text{ lbs}$$

in agreement with the directly measured weight loss of the ice pile.

DISCUSSION OF Q_{in}

The quantity Q_{in} has been identified as being characteristic for the subsystem which generates the gas flow. For a gas dump the behavior of the system is completely described by equations 2 and 3. Next we shall present the case of a liquid dump. To give an example how Q_{in} depends on different quantities, the variation of Q_{in} during the socalled "biocide dump" will be discussed. It entails the release of 57 lbs of slightly contaminated water at a rate of 2 lbs/min which is equivalent to a mass flow rate

$$\dot{m}_o=15.1 \text{ [g sec}^{-1}] \tag{32}$$

From data taken during this event Q_{in} can be calculated from equation 2 as

$$Q_{in}=C\Delta P+V_1\dot{P} \tag{33}$$

The results are shown in figure 8 where Q_{in} is plotted as a function of the waste tank pressure. The data points are further characterized by the time (minutes:seconds) after the biocide dump was started. One should add, however, that the water flow through the nozzle did not start before (10:12).

One can assume that the main energy source for sublimation during the dump is the stream of water. By comparison other heat transfer mechanisms do not contribute to the sublimation rate Q_{in} to any appreciable extent. Due to its low heat capacity the presence of the baffle can also be neglected for our purposes. We make the further assumption that the temperature of the water upon entering the waste tank is 22°C and that the pressure is well below the pressure at the triple point (4.58 torr). Then one can estimate that about 16 percent of the total mass flow rate $\dot{m}_o$ gives rise to a vapor flow rate Q_{in}(theory), while 84 percent of the water flow will be deposited as ice on the baffle with a temperature close to the freezing point. Therefore the mass flow rate, $\dot{m}_s$, of the sublimated water vapor is

$$\dot{m}_s=0.16\ \dot{m}_o=2.42 \text{ [g sec}^{-1}] \tag{34}$$

which is equivalent to

$$Q_{in}(\text{theory})=2.28x10^3 \text{ [torr } \ell\text{sec}^{-1}] \tag{35}$$

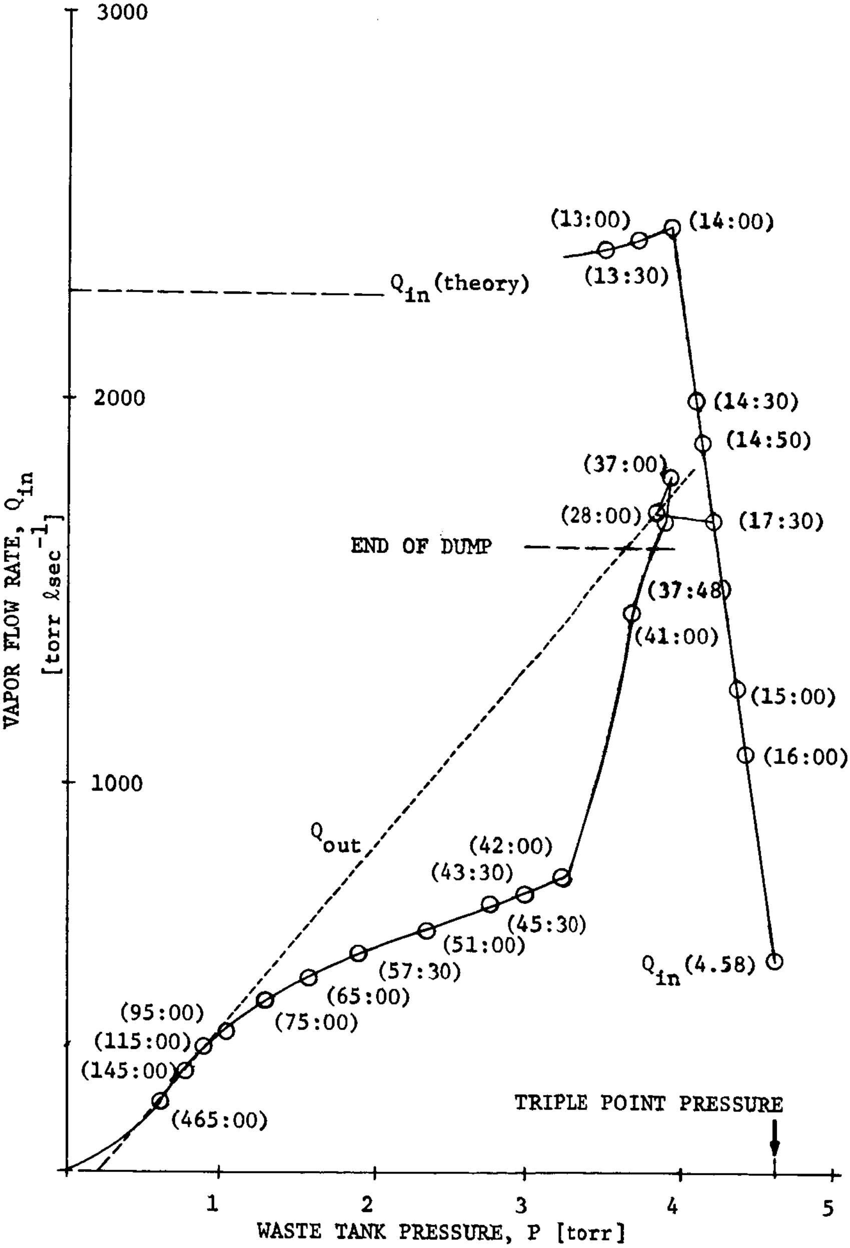

Figure 8. History of a Biocide Dump

which is shown as a dashed line in figure 8.

Q_{in}(theory) is in reasonable agreement with the experimental values observed at (13:00), (13:30) and (14:00).

After (14:00) a drastic decrease of Q_{in} is observed. This fast drop of Q_{in} has obviously to do with the fact that at this point the pressure in the waste tank has risen to a value where the sublimation rate of the dumped water is significantly reduced. This leads to the conclusion that not all of the dumped water will be frozen immediately and that water close to the freezing point will reach the ice pile.

A close look at the experimental points in figure 8 between (14:00) and (17:30) shows that these values can readily be connected by a straight line which, when extrapolated to the pressure P_T=4.58 torr at the triple point, yields

$$Q_{in} \approx 500 \ [\text{torr } \ell \text{sec}^{-1}] \tag{36}$$

By comparison one can calculate Q_{in} which is expected at the triple point for a mass flow rate $\dot{m}_o$=15.1 g $\sec^{-1}$ and a water temperature of 22°C. One finds

$$Q_{in}(4.58) = 560 \ [\text{torr } \ell \text{sec}^{-1}] \tag{37}$$

in reasonable agreement with the experimental value estimated above.

What is more interesting, however, is the constant rate of change for $Q_{in}(P)$ which is suggested by the straight line interpolation. One finds for the time interval (14:00) to (17:30)

$$\frac{dQ}{dP} \approx -2800 \ [\ell \text{sec}^{-1}] = -2.8 \ [\text{m}^3 \text{sec}^{-1}] \tag{38}$$

In order to connect this value with the theoretical expectation one can derive a relation between the equilibrium vapor pressure P_o and the deviation δP from equilibrium in a steady state condition as a function of the pumping speed, S, the surface area of the source, A, the average thermal velocity of the water molecules, v_{av}, and the sticking coefficient, s (Reference 2). It is

$$\delta P = -\frac{SP}{Av_{av}} \cdot \frac{4}{s} \approx -\frac{Q_{in}}{Av_{av}} \cdot \frac{4}{s} \tag{39}$$

Therefore

$$\frac{dQ_{in}}{d\delta P} = \frac{dQ_{in}}{dP} = -\frac{1}{4} Av_{av} s \tag{40}$$

Reference 2 G. Rupprecht, "Steady State Solutions Concerning the Lox-Tank Venting System," Contract MC8-824000, December 1971

The average thermal velocity of water molecules at 0°C is v_{av}= 615 $msec^{-1}$. Through the evaluation of photographs taken during the dump the surface area of the ice pile can be estimated to $A \simeq 1m^2$. Therefore the sticking coefficient becomes:

$$s=-4(\frac{dQ_{in}}{dP}) \cdot \frac{1}{Jv_{av}} = \frac{4x2.8}{1x615} = 1.8x10^{-2} \tag{41}$$

Delaney et al., (Reference 3), have obtained the value $s=1.44x10^{-2}$ in the temperature range between -2°C and -13°C, while H. Patashnick and G. Rupprecht in a recent study found $s=2x10^{-2}$ for ice particles close to the triple point. Considering the uncertainty in the estimate of the surface area of the ice pile, the value obtained here fits well into the range of expected s values.

The straight line in figure 8 connecting the experimental value between (14:00) and (17:30) constitutes an upper limit for Q_{in}.

After some strong fluctuations on the part of Q_{in} the situation stabilizes and comes to a quasi steady state condition after (17:30) which lasts to the end of the dump at (37:48) when the water flow stops. During this time interval, the values for P and Q_{in} hover around 3.8 torr and 1700 torr ℓsec^{-1}, respectively. One can evaluate these values to calculate the pumping speed as

$$S= \frac{1700 \text{ torr } \ell sec^{-1}}{(3.8-0.2) \text{ torr}} =472 \ \ell sec^{-1} \tag{42}$$

a value which is slightly larger than the previously determined value for water vapor at lower pressures. See equation 23.

At the end of the dump at (37:48), Q_{in} drops again quite drastically and remains in a transient condition, $(Q_{in}<Q_{out})$. What is changing in this time interval is the temperature of the ice pile which decreases from near freezing to about -32°C. This temperature change has been observed directly with a thermocouple underneath the ice pile. The sublimation energy during this transient time interval stems mainly from the ice pile which acts as a energy storage. In order to check this assumption a simple estimate can be carried out.

For about 4 minutes and 30 seconds, Q_{in} is close to the theoretical value of 2280 torr ℓsec^{-1}. During this time, 3.5 kg of ice are generated. In the following 24 minutes when ice and water are generated, one can define the fraction μ as

$$\mu= \frac{Q_{in}(\text{experiment})}{Q_{in}(\text{theory})} \approx \frac{1700}{2280} =0.75 \tag{43}$$

Reference 3 L. F. Delaney & R. W. Houston & L. C. Eagleton, "The Rate of Vaporization of Water and Ice," Chemical Engineering Science, 1964, Vol. 19, Pg. 105-114

and calculate that under these circumstances the fraction of ice, i, and the fraction of water, w, which are produced. One finds

$$i = \frac{1}{L}\left\{\mu\cdot \frac{(\Delta T+L)(\Delta T+H)}{\Delta T+L+H} - \Delta T\right\} = 0.52 \tag{44}$$

$$w = \frac{1}{L}(1-\mu)(\Delta T+L) = 0.35 \tag{45}$$

H is the energy of sublimation in [cal g^{-1}], L the latent heat in [cal g^{-1}], $\Delta T \approx 32°K$. At the end of the dump one has 14.5 kg of ice mixed with 7.4 kg of water at the freezing point which can deliver upon cooling the total energy of

$$E_s' = (21.9\text{x}32\text{x}0.49+7.4\text{x}80)\text{kcal} = 935 \text{ kcal} \tag{46}$$

On the other hand one can estimate the sublimation energy from Q_{in} during the time interval (38:00) to (80:00), assuming that by (80:00) the majority of the stored energy has been spent. Through integration one finds

$$E_s = \int_{(38:00)}^{(80:00)} Q_{in}dt \approx 1.62\text{x}10^6 \text{ torr } \ell = 925 \text{ kcal} \tag{47}$$

A comparison between E_s and E_s' shows reasonable agreement between the two values and strongly suggests that the ice pile is indeed the essential source of sublimation energy. For this reason the temperature distributions of the surrounding is of negligible influence during and after the dump up to this point in time.

Later, however, as a quasi steady state condition is approached, the radiative heat transfer to the ice pile becomes important and to a lesser degree the heat transport due to the heat diffusion through the moving vapor. These problems concerning the quasi steady state condition a long time after the dump have been treated elsewhere (Reference 2).

Instead we shall report the observation of a phenomenon which was quite unexpected. It pertains to the influence of CO_2 gas on the sublimatation rate of the ice pile, i.e., on Q_{in}. The original idea was to probe Q_{in} independently with a simple method which is insensitive to the bias of the instrumentation. For this purpose CO_2 gas was admitted through the nozzle until the pressure in the waste tank had risen to a certain level ($\approx$1 torr). Then the gas was shut off. The assumption was that the ice pile would produce Q_{in} just as before the admission of CO_2. The concentration of water vapor in the upper compartment would first become much greater than in the rest of the tank. Therefore (k_1) in equation 2 would be different from (k_2) in equation 3. With increasing time, however,

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the CO_2 gas in the waste tank would be replaced entirely by water vapor and $(k_2) \rightarrow (k_1)$. The time it takes to replace the CO_2 gas by water vapor was thought to be a convenient measure of the sublimation rate of the ice pile, i.e., a measure of Q_{in}. It did not work out as planned, however.

The observation is reported in figure 9. Prior to time t=0, the pressure was held constant for a short while at $P_m \approx 1$ torr by admission of CO_2 at an appropriate flow rate. At the same time the pressure drop ΔP_m across the upper screen was constant at $\Delta P_m = 11.7$ mtorr. At t=0 the CO_2 gas flow is stopped. As a consequence ΔP_m drops immediately to about 2 mtorr; drops a bit more and rises to a constant level after 30 minutes. The pressure on the other hand decreases continually as is also shown in figure 9, to a constant level about 30 minutes later. The slight drop of ΔP_m in the first few minutes can be understood on the basis that $C(H_2O) < C(CO_2)$, and that it takes some time to clear the upper compartment of CO_2 gas. A rise of ΔP_m on the other hand is expected because $S(H_2O) > S(CO_2)$. The solution of equations 2 and 3 for the proper boundary conditions concerning (k_1) and (k_2) has been carried out for a sequential series of experiments considering Q_{in} as the unknown. The result of these calculations is shown in figure 10. After a dump of 10 lbs of condensate on top of an existing ice pile, Q_{in} is shown as a function of pressure. As the pressure has decreased to about 0.7 torr, CO_2 gas is added to bring the pressure up to about 1 torr. Then the CO_2 flow is shut off. Q_{in} is now supplied solely by the ice pile. While it was expected that Q_{in} would be unaffected by the presence of the CO_2 gas the experiment clearly shows a strong reduction of Q_{in} marked as Event #25. As time passes, Q_{in} recovers to its original value. In subsequent events, for lower H_2O pressure the effect of a CO_2 purge becomes even more pronounced. This observation shows that the presence of various gases and vapors may have a pronounced effect on the sublimation rate of the waste tank content and opens the possibility of influencing the contamination of the space environment. Of course, under these circumstances the use of CO_2 as a probe for Q_{in} had to be abandoned.

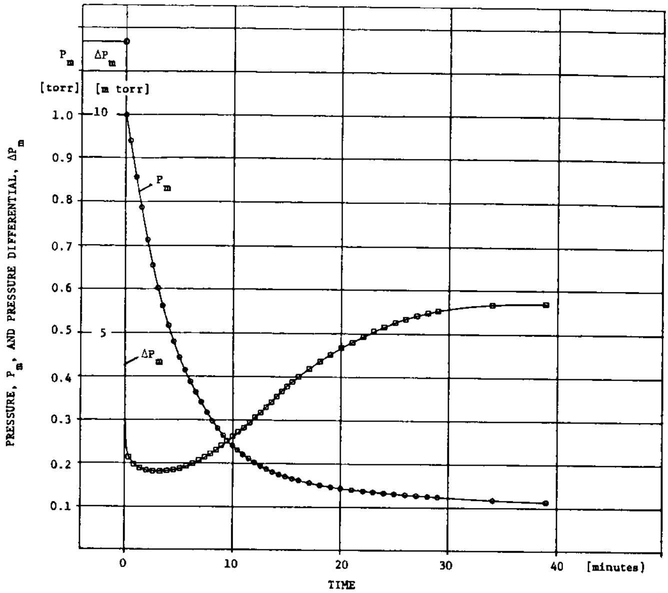

Figure 9. Time Dependence of the Tank Pressure, P_m, And of the Pressure Differential ΔP_m After a CO_2 Purge

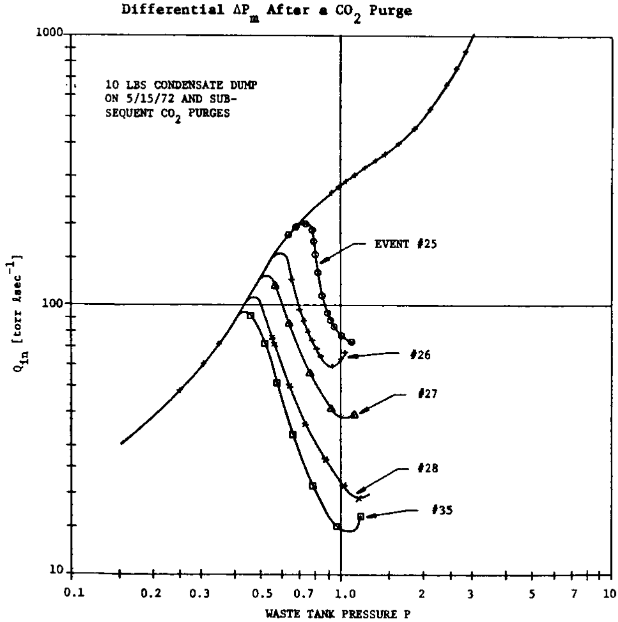

Figure 10. The Effect of CO_2 Gas on the Sublimation Rate of Ice

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